ENGINEERING

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Technical Note

CRSI Concrete Reinforcing Steel Institute

Fire Resistance of Reinforced Concrete Buildings

Introduction

Among the many unique virtues of cast-in-place reinforced concrete buildings are:

Structural Integrity (continuity) - ability of a structure through strength, redundancy, ductility, and detailing of reinforcement to redistribute stresses and maintain overall stability if localized damage or significant overstress occurs [ACI 318 (2014)]. Structural integrity in a building provides alternate load paths in the event of damage to a major supporting member or an abnormal loading event. The ACI 318 Building Code includes requirements for structural integrity (Sections 4.10, 8.8.1.6, 9.7.7, and 9.8.1.6).

Fire resistance – the property of a material or assembly to withstand fire or provide protection from it. As applied to elements of buildings, it is characterized by the ability to confine a fire or, when exposed to fire, to continue to perform a given structural function, or both [ACI 216.1 (2014)]. Reinforced concrete is inherently fire resistant. Cast-in-place reinforced concrete buildings have a good track record from a fire resistance standpoint.

This report focuses on the fire resistance aspects of reinforced concrete buildings.

Fires have shown their ability to do great harm to life and property whether through arson, by accident, or by nature. Historically, some of the more notable fires that have involved hundreds of buildings are: Boston, 1631, 1653, 1679, 1872; Charleston, 1740; Detroit, 1805; New York, 1835; Savannah, 1840; Albany, 1848; Pittsburgh, 1845; San Francisco, 1849, 1851, 1906; Philadelphia, 1850; Chicago, 1871; Hoboken, 1900; Jacksonville, 1901; Baltimore, 1904; Salem, Mass., 1914; Paris, Texas, 1916; and Atlanta, 1917.

Some of the more notable individual building fires where significant loss of life has occurred are the Iroquois Theater, Chicago, 1903; Triangle Shirtwaist Factory, New York, 1911; Lakeview Grammar School, Ohio, 1908; New London School, Texas, 1937; Our Lady of Angels School, Chicago, 1958; Rhythm Club, Natchez. Miss., 1940; Coconut Grove, Boston, 1942; Beverly Hills Supper Club, Southgate, Ky., 1977; MGM Grand, Las Vegas, 1980; Stouffer's Inn, New York, 1980; Happy Land Social Club, New York, 1990; World Trade Center, New York, 2001; and The Station nightclub, Rhode Island, 2003.

Even without a single major event in a given year, fires account for a significant personal and economic drain. In 2013, according to the National Fire Protection Association (NFPA), over 1.2 million fires occurred, resulting in more than 3,200 civilian deaths, over 15,900 civilian injuries, and over $11.5 billion dollars in direct property loss ([NFPA (2014)]. Of these 1.24 million fires, 487,500 were structure fires, causing 2,855 civilian deaths, 14,074 civilian injuries, and $9.5 billion in property loss.

NFPA's figures for the year 2001 reflect the devastation caused by the terrorists' attack on the World Trade Center. In 2001, fires caused over 6,600 deaths and over 44 billion dollars in property damage – 2,666 deaths and some 33 billion dollars in property losses were attributed to the destruction of the World Trade Center. NFPA's property damage figures are direct losses; the figures do not include indirect losses such as business interruption. Also the cost figures have not been adjusted for inflation.

Since fires are a major hazard, as related by history and the preceding grim statistics, the fire resistance of buildings is important in the protection of life and property against the hazards of fires. To mitigate a fire hazard, building codes regulate various aspects of building construction including requirements for noncombustible materials, and fire resistance classifications depending on building use, occupancy, size and location.

The World Trade Center disaster has generated considerable debate about code requirements and issues related to the hazards of fire. In the Nov.-Dec. 2002 issue of

Southern Building Magazine, J. J. Messersmith, Jr. authored an informative article "Structural Fire Resistance for Tall Buildings: Past and Present". The article focused on the history of fire rating requirements in the model and several major city building codes, and the trend towards the reduction of fire ratings. Mr. Messersmith attributed the relaxing of the fire rating requirements to (1) a belief by some parties that the earlier codes were too conservative, and (2) encourage the use of automatic suppression devices. The latter item can be characterized as "trade-offs".

Philosophically, CRSI supports a balanced approach to mitigate the hazards of fire in buildings. A balanced approach consists of (1) automatic detection or warning devices; (2) fire resistance of the material itself plus the fire resistance of the structural system; and (3) automatic suppression devices.

Building Codes

Currently, the two model building codes are: *International Building Code*, 2015 [ICC (2015)]; and *NFPA 5000 Building Construction and Safety Code* [NFPA (2015)]. Because of space limitations, only the fire resistance requirements in the *International Building Code* (IBC) are cited in this report.

Definitions of Terms

Fire-Resistance Rating or **Fire Rating:** The *International Building Code* [ICC (2015)] defines fire-resistance rating (paraphrased) as the period of time (usually expressed in hours) a building element (a structural member), component or assembly maintains the ability to confine a fire, continues to perform a given structural function or both, as determined by the tests, or the methods based on tests, prescribed in Section 703.

Noncombustible Material: A material that, under the conditions anticipated, will not ignite or burn when subjected to fire or heat. Materials that pass ASTM E136 are considered noncombustible materials.

Restrained: A condition in which the expansion at the supports of a load-carrying member resulting from the effects of a fire is resisted by forces external to the member. Restraint may be provided by the lateral stiffness of supporting members for floor and roof structural members and systems. To provide restraint, connections with the supporting members must adequately transfer thermal thrusts to the supports. All cast-in-place reinforced concrete floors and roofs, which are monolithically cast with their supporting members (columns or walls), are considered to be restrained. For example, single spans, which are uncommon in cast-in-place reinforced concrete construction, are considered to be unrestrained. (See ASTM E119, Appendix X.3 for additional information related to determining thermal restraint conditions).

Unrestrained: A condition in which the load-carrying member is free to expand and rotate at the supports resulting from the effects of a fire.

ASTM E119 Fire Test

The tests cited in the *IBC* definition of fire-resistance (fire) rating refer to ASTM E119, "Standard Test Methods for Fire Tests of Building Construction and Materials" [ASTM (2014)]. According to ASTM E119, assemblies are subjected to a fire that follows a standard time-temperature curve. The fire-resistance rating of an assembly is determined by the duration of the test until one of the following end-points is reached:

1. Cotton waste ignites as a result of flames or hot gases passing through holes, cracks or fissures in the assembly. (Flame passage end-point.)
2. The temperature of the unexposed surface of the assembly rises an average of 250°F or a maximum of 325° F at any one point. (Heat transmission end-point.)
3. The test specimen is unable to sustain the applied loading - collapse is an obvious end-point. (Structural end-point.)

Additional fire-resistance rating criteria include:

- For unrestrained reinforced concrete members, in some cases, the average temperature of the tension reinforcement at any section must not exceed 1100°F. For restrained reinforced concrete beams spaced more than 4 feet on centers, the 1100°F temperature must not be exceeded for fire ratings of one hour or less; for fire ratings longer than one hour, the 1100°F temperature must not be exceeded for the first half of the rating period or one hour, whichever is longer. Restrained beams, spaced 4 feet or less on centers, and slabs are not subjected to the 1100°F temperature limit.
- For walls, the ability to resist the impact, erosion, and cooling effects of a specific size hose stream. This criterion is intended to emulate a fire hose.

Non-Combustibility

In the IBC there are five types of construction. Type I and II construction are those types of construction in which the building elements listed in Table 601 are of noncombustible materials. Type III is wood frame with noncombustible or fire-retardant treated wood exterior walls, Type IV is heavy timber, and Type V is generally thought of as wood frame.

Combustibility of materials are typically determined using ASTM E136 Standard Test for Behavior of Materials in a Vertical Tube Furnace at 750° C. The test has two passing criteria. Under Passing Criteria #1:

a. Weight loss of the specimen cannot exceed 50%.

b. Temperatures on the surface of the specimen and at the geometric center of the specimen during the test may not rise more than 54° F above the equilibrium temperature of the furnace measured prior to introducing the specimen. During the first 30 seconds of the test, there can be no flaming from the specimen.

In Passing Criteria #2:

a. If more than 50% of the weight of the specimen is lost, the material may still be classified as non- combustible provided both of the following conditions are met.

b. Temperatures on the surface of the specimen and at the geometric center of the specimen during the test may not rise above the equilibrium temperature of the furnace measured prior to introducing the specimen.

c. No flaming from the specimen can occur at any time during the test.

Concrete and steel exceeds the requirements to be defined as non-combustible,

Reinforced concrete performs well in a fire – both as an engineered structure, and as a material with inert (non-combustible) properties. Concrete's inherent material properties minimize fire risk for the lowest initial cost while requiring the minimum ongoing maintenance over the lifetime of the project. Reinforced concrete does not require any additional fire-protection because It is a non-combustible material (i.e. it does not burn) and has a slow rate of heat transfer.

Fire tests of beams constructed with normal weight concrete with 12" width and typical 2.5" inch cover have shown that for exposures up to 2 hours the temperature inside the concrete in the vicinity of the steel reinforcement reaches approximately 600° to 700° F. At these temperatures, there is minimum loss of flexural strength thus ensuring that structural integrity is not compromised during a fire.

Analytical Methods for Determining Fire Ratings

The results of many ASTM E119 standard fire tests on reinforced concrete members have been compiled and analyzed over many years. Along with standard fire tests, there has been research and development of data on the strength of reinforcing steel and concrete at elevated temperatures; the temperature distribution within concrete, the verification and modification of theory, and the effects of restraining thermal expansion during heating. This extensive testing and research forms the basis for analytical methods of determining the fire ratings for reinforced concrete structural members. Determining fire ratings can be classified into rational design and empirical design.

Rational Design

In rational design, the fire rating is the time required for the load capacity of the member to be reduced to equal that of the service loads. The rational design process for fire exposure has been included as an acceptable alternative to prescriptive methods in applicable codes and standards enforced in Europe, Australia, and New Zealand since at least 1990. Documents such as the EN 1991-1-2, Eurocode 2: Design of concrete structures — Part 1-2: General rules — Structural fire design, Australian Standard AS 3600, Concrete structures include provisions for rational design, and NZS 3404, Concrete Structures Standard (which references Eurocode 2) provide detailed provisions for calculating a fire resistance rating using a rational design approach. United States building codes have been slow to adopt similar provisions, however designers are permitted to present the results of a rational analysis for fire resistance ratings as an alternate method compliance

Rational design involves three distinct steps or phases to determine the adequacy of a particular assembly to withstand the effects of fire. Part one involves defining the exposure fire incident on the assembly, part two involves calculating the heat transfer into the assembly, and part three is a structural analysis using degraded material properties at an elevated temperature to determine the period of structural adequacy.

The fire or exposure temperature may be from the ASTM E119 standard time-temperature curve or another source if agreed upon with the building official as an alternate method of compliance. Heat transfer into the assembly may be determined by calculation using simplified methods such as tables or lumped thermal capacity models, or more advanced methods employing finite element programs in two or three dimensions to establish the temperature profile within the assembly.

Appendix C2.5 from ASCE 07, *Minimum Design Loads for Buildings and Other Structures* proposes load combinations for checking the capacity of a structure or structural element to withstand the effect of an extraordinary event such as fire which is characterized by a low probability of occurrence and usually a short duration. Load combinations include the following cases:

1.2 Dead + (0.5 Live or 0.2 Snow)
(0.9 or 1.2) Dead + 0.2 Wind

The structural analysis treats fire as an imposed load and follows the same procedures that would be used under normal conditions substituting modified values for concrete compressive strength, yield strength of reinforcing steel, and modulus of elasticity for both materials at elevated temperatures. The effects of support conditions, restraint due to thermal expansion, and load re-distribution can be accounted for in the analysis. The fire resistance rating is determined as the time the assembly can safely support the imposed loads without failure.

Detailed design examples of the structural analysis at elevated temperatures for reinforced concrete assemblies can be found in the CRSI book, *Reinforced Concrete Fire Resistance [CRSI (1980)],* ACI 216.1, *Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies*, and "Structural Design for Fire Safety," among others.

Empirical Design

Empirical design uses the results of ASTM E119 fire tests, such as data on the strength of heated reinforcing steel and concrete, and the temperature distribution in concrete to establish critical member thickness, concrete cover, and so on. Application of empirical design is simpler than rational design, since structural analyses are not required. For cast-in-place reinforced concrete, the term "empirical design" is somewhat of a misnomer. A more accurate term would be "empirical approach" since there is not any design involved. Conforming to code requirements merely involves providing the required concrete cover for the reinforcement, determining the required thickness of the member, and so on.

Walls: The fire ratings of reinforced concrete walls are nearly always governed by the heat transmission end-point before allowing passage of flame or failing structurally. Table 1 lists the minimum reinforced concrete wall thicknesses, for different types of aggregates, to provide the required fire ratings.

Floors and Roofs: Similar to walls, the fire ratings of reinforced concrete floors and roofs are often governed by the heat transmission end-point. Thus, Table 1 is also applicable for reinforced concrete floors and roofs. Table 2 lists the required concrete cover, based on type of aggregate and restraint condition, to provide the required fire rating.

Joists: For standard joist construction, the equivalent thickness is based on the spacing of the ribs and thickness of the top slab. The equivalent thickness is determined (see Fig. 1):

For $s \geq 4t$, the equivalent thickness is t

For $s \leq 2t$, the equivalent thickness is t_e

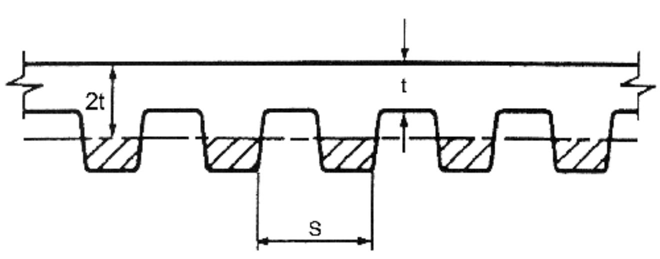

Figure 1 – Equivalent thickness for joist construction.

For $4t > s > 2t$, the equivalent thickness is $t + (4t/s - 1)(t_e - t)$

Where: s = center-to-center spacing of ribs

t = top slab thickness

t_e = thickness of the joist section, calculated as the net cross-sectional area divided by the rib spacing, in which the maximum thickness used in the calculation does not exceed 2t.

For wide-module joist construction (ACI 318 Code, Sections 8.8 or 9.8), the equivalent thickness equals the top slab thickness. Tables 1 and 2, which are used for floor and roof slabs, would also be applicable for reinforced concrete joists, with the joist's equivalent thickness used in Table 1.

Beams: The fire ratings of beams depend on concrete cover, the width of the cross section, and the restraint condition (Table 3).

Columns: The fire rating of a reinforced concrete column is influenced primarily by the column size and the aggregate type. The fire ratings of columns are related to minimum column size (Table 4) and minimum concrete cover requirements (Table 5).

The preceding discussion of the prescriptive requirements in the *International Building Code* illustrates the "supply side" of the equation. Let us examine briefly the "demand side" for a hypothetical office building – based on the *IBC*. The *IBC* mandates the most stringent fire resistance requirements for what is classified as Type 1A construction. While a Type 1A building can be of unlimited height and area, it has to be built with non-combustible materials. The *IBC* also prescribes, for a Type 1A building, fire-resistance ratings of: 3 hours for the structural frame including columns, girders and trusses; 3 hours for bearing walls; 2 hours for floors including supporting beams and joists; and 1.5 hours for the roof (IBC, Table 601). If the structural frame or bearing walls support a roof only, the ratings can be reduced by one hour.

Benefits of Reinforced Concrete Construction for Fire Endurance

Cast-in-place reinforced concrete construction provides buildings with excellent fire endurance. In an actual fire, reinforced concrete floors and walls are likely to remain in place longer than the time reflected by their ASTM E119 fire ratings, since their fire resistance rating is typically determined by the heat transmission end-point of the E119 fire test. In most cases, just how long the walls and floors will continue to perform is unknown, because the fire tests are often ended prior to structural failure.

Additional reasons why cast-in-place reinforced concrete is the material of choice for mitigating the fire hazard:

1. Reinforced concrete is composed of inherently fire-resistant, non-combustible materials.
2. Reinforced concrete construction does not require additional costly fireproofing.
3. The redundancy of cast-in-place reinforced concrete structural systems effectively resists the attack of a fire.
4. Connections of reinforced concrete structural members, e.g., beam-column joints, are not vulnerable to fire. Such connections do not require specially constructed additional protection.
5. The lower fire risk for both the occupants and the building typically qualifies reinforced concrete construction for lower insurance rates than either structural steel or wood frame buildings.
6. Reinforced concrete fire walls and fire separations contain fires to where they start, reducing potential fire losses to the building and its contents.
7. Reinforced concrete is not readily damaged by fire, which means that in most cases only a clean-up, rather than extensive repairs, will be all that is needed to put the building back in service.
8. In most instances, maintaining normal design and construction practices for cast-in-place reinforced concrete results in a multi-hour fire rating at no additional expense or effort.

Table 1 – Minimum Equivalent Thickness for Reinforced Concrete Walls, Floors and Roofs

Aggregate Type	Minimum Thickness (in.) for Fire Rating of				
	1 hr	1½ hr	2 hr	3 hr	4 hr
Siliceous	3.5	4.3	5.0	6.2	7.0
Carbonate	3.2	4.0	4.6	5.7	6.6
Sand-Lightweight	2.7	3.3	3.8	4.6	5.4
Lightweight	2.5	3.1	3.6	4.4	5.1

1 inch = 25.4 millimeters Source: IBC Tables 722.2.1.1, 722.2.2.1

Table 2 – Minimum Concrete Cover for Reinforced Concrete Floor and Roof Slabs

Aggregate Type	Minimum Concrete Cover (in.) for Fire Rating of					
	Restrained	Unrestrained				
	4 hr or less	1 hr	1½ hr	2 hr	3 hr	4 hr
Siliceous	¾	¾	¾	1	1¼	1⅝
Carbonate	¾	¾	¾	¾	1¼	1¼
Sand-Lightweight or Lightweight	¾	¾	¾	¾	1¼	1¼

1 inch = 25.4 millimeters Source: IBC Table 722.2.3(1)

Table 3 – Minimum Concrete Cover for Reinforced Concrete Beams[1]

Restraint[2]	Beam Width[3] (in.)	Minimum Concrete Cover (in.) for Fire Rating of				
		1 hr	1½ hr	2 hr	3 hr	4 hr
Restrained	5	¾	¾	¾	1	1¼
	7	¾	¾	¾	¾	¾
	≥10	¾	¾	¾	¾	¾
Unrestrained	5	¾	1	1¼	NP	NP
	7	¾	¾	¾	1¾	3
	≥10	¾	¾	¾	1	1¾

1 inch = 25.4 millimeters Source: IBC Table 722.2.3(3)

Notes:
1. The concrete cover for an individual reinforcing bar is the minimum thickness of concrete between the surface of the bar and the fire-exposed surface of the beam. For beams in which several bars are used, the concrete cover for corner bars used in the calculation shall be reduced to one-half of the actual value. The concrete cover for an individual bar must not be less than one-half of the value given in the table, nor less than 3/4 inch.
2. Tabulated values for restrained assemblies apply to beams spaced more than 4 feet on center. For restrained beams spaced 4 feet or less on center, a minimum concrete cover of 3/4 inch is adequate for a fire rating of 4 hours or less.
3. For a beam width between the tabulated values, the minimum concrete cover can be determined by interpolation.
4. "NP" = Not Permitted.

Table 4 – Minimum Size of Reinforced Concrete Columns

Aggregate Type	Minimum Column Size (in.) for Fire Rating of				
	1 hr	1½ hr	2 hr	3 hr	4 hr
Siliceous	8	9	10	12	14
Carbonate	8	9	10	11	12
Sand-Lightweight	8	8½	9	10½	12

1 inch = 25.4 millimeters Source: IBC Tables 722.2.4

Notes:
1. For 2-hour and 3-hour fire ratings, the minimum dimension can be reduced to 8 inches for rectangular columns with two parallel sides at least 36 inches in length.
2. For a 4-hour fire rating, the minimum dimension can be reduced to 10 inches for rectangular columns with two parallel sides at least 36 inches in length.

Table 5 – Minimum Concrete Cover for Reinforced Concrete Columns

Aggregate Type	Minimum Concrete Cover (in.) for Fire Rating of				
	1 hr	1½ hr	2 hr	3 hr	4 hr
Siliceous	1	1½	2	2	2
Carbonate	1	1½	2	2	2
Sand-Lightweight	1	1½	2	2	2

1 inch = 25.4 millimeters Source: IBC Section 720.2.4.2

Notes:
1. Concrete cover is measured to the main longitudinal reinforcement in the column.

Resources

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